Phase and frequency noise metrology

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Frequency standards are now attaining the stability of 10^{-16} to 10^{-17} (Allan deviation σ_y) in favorable conditions. Yet, our ability to transfer and to measure the reference frequency, or it fluctuations, and to craft flywheel oscillators is at the present time insufficient. Though this sub-domain is inherently modest as compared to fundamental metrology and physics, it turns out to be difficult in practice. One reason is that it relies on experimental skill, while theory gives only very few and general indications. Another reason is that flicker ($1/f$) noise makes the difference. Flicker is not understood and not accepted in fundamental physics, and sometimes referred to as "technical noise." We all remember that in the '90s dozens of Cs fountains were on the stage, and that only 3–4 teams were tackling the sapphire oscillator flywheel. Interestingly, the flicker of the sapphire resonator has still not been measured.

Optics is not replacing microwaves. Instead, the emerging domain of microwave photonics is providing challenges and solutions. For frequency comparisons up to 100 km distance, a two-way optical-fiber microwave link is the only viable solution. This is also inevitable to compare two signals originated from separate tables in the same room in extreme experiments, demanding $\sigma_y \sim 10^{-17}$. Similar solutions are under study for electron accelerators (DESY), where synchronization at 20–50 fs level is required over the size of the plant, a few km. Of course, the success relies on the ability to measure phase noise in real time, and to achieve low $1/f$ background noise.

The article reviews the techniques for the measurement of phase noise providing the highest sensitivity in the RF/microwave region. The extension to frequency measurement is obvious. In favorable conditions, a signal (the noise of a device under test) of 10^{-17} rad^2/Hz, flicker at 1 Hz off the 10 GHz carrier, can be measured in single-channel mode, thus in real time, well above the background noise. This value is equivalent to a length fluctuation $\sigma_L = 1.25\times10^{-11}$ m (Allan deviation). For reference, the Bohr radius of the electron is $a_0 = 5.29\times10^{-11}$. In microwave photonics, the flicker seems to be limited by the $1/f$ noise of the photodetector, of the order of 10^{-12} rad^2/Hz at 1 Hz, equivalent to a length fluctuation $\sigma_L\times \sim 4\times10^{-9}$ m. Correlation and averaging improves the sensitivity. The ultimate background, still not known, is certainly lower than 10^{-21} rad^2/Hz, white noise. The correlation technique has also been used for the measurement of amplitude noise, where the literature on experimental methods is extremely poor, and of course for the measurement of the laser RIN. As an example, the $1/f$ amplitude noise of a quartz oscillator, converted into Allan deviation $\sigma_{\Delta V/V}$, can be of parts in 10^{-7}. Experiments provide insight and a phenomenological description of flicker in electronics and microwave photonics. It turns out that phase flickering tends to be independent of the signal power, and to add up independently of the order of the stages in a chain. This contradicts the common belief that the most critical stage of a low-noise chain is the front-end.

Besides the obvious application to oscillators and frequency standards, the reported techniques and results provide rules for the design of complex systems.